Improving Efficiency and Load Range of Boosted HCCI using Partial Fuel Stratification with Conventional Gasoline

John Dec,
Yi Yang and Nicolas Dronniou
Sandia National Laboratories

Sponsor:
U.S. DOE, Office of Vehicle Technologies
Program Manager: Gurpreet Singh

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Motivation

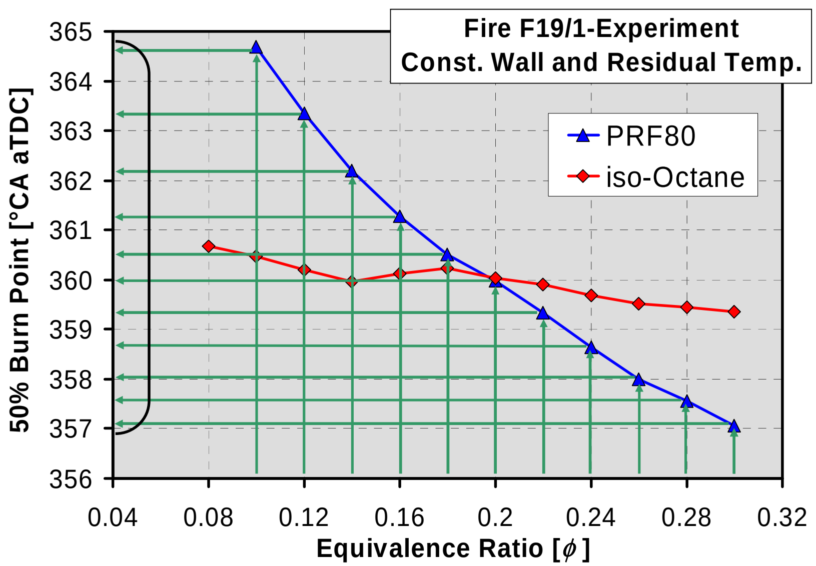
- Advanced engines using HCCI or HCCI-like combustion can provide both high efficiencies and very low emissions of NO_X and PM.
- Limited max. power is a significant limitation to implementation of HCCI.
- Recent results (SAE 2010-01-1086) show that intake boosting is a viable approach for extending the high-load limit of gasoline-fueled HCCI.
  – Achieved loads up to 16.3 bar $IMEP_g$ without engine knock & ultra-low NO_X.
  – Knock controlled by retarding combustion phasing.
- **Improvements are desirable in two key areas:**
  1. Reducing PRR with less combustion retard would allow higher loads with less boost.
     > Greater operational flexibility and reduce pumping work for higher net eff.
     > Increase exhaust enthalpy for a given boost, easing turbo-charger design.
  2. Even higher efficiencies could be achieved if less timing retard was required to control knock.

- Significant potential advantages to reducing PRR without timing retard.

Partial Fuel Stratification (PFS)

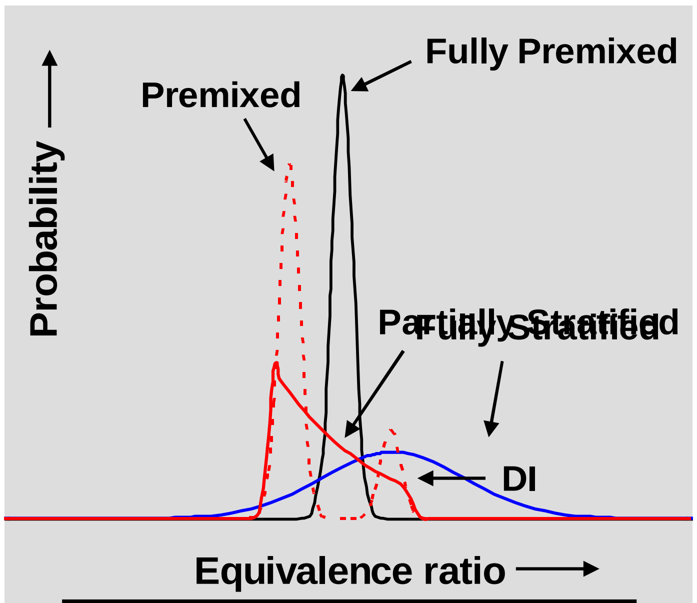
- One promising technique for reducing PRR is partial fuel stratification.
- Effective for controlling HRR (and PRR), but has two requirements:

1) Fuel autoig. must be ϕ-sensitive



Dec and Sjöberg, SAE 2004-01-0557

2) Appropriate ϕ-distribution



Sjöberg and Dec, SAE 2006-01-0629

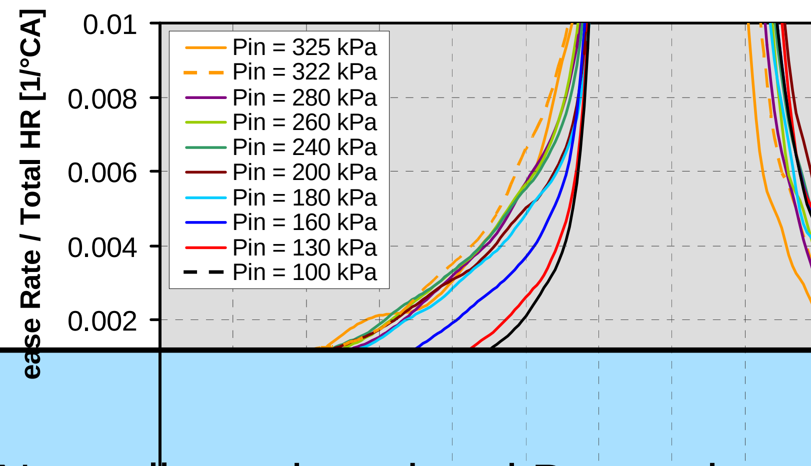
- PRF80 is strongly ϕ-sensitive (2-stage ig.), iso-octane is not (1-stage-ig.)
- Partial fuel stratification (PFS) ⇒ most fuel premixed, up to 20% late DI.
  1. Good air utilization with leanest regions burning hot enough for good comb.
  2. Provides sufficient stratification.

PFS - Fuel Effects (ϕ-Sensitivity)

- Previous studies (naturally aspirated) have shown that PFS:
  - Reduces HRR for fuels with 2-stage ignition ⇒ high reactivity (ϕ-sensitive).
  - Ineffective for fuels with 1-stage ignition ⇒ low reactivity (not ϕ-sensitive).

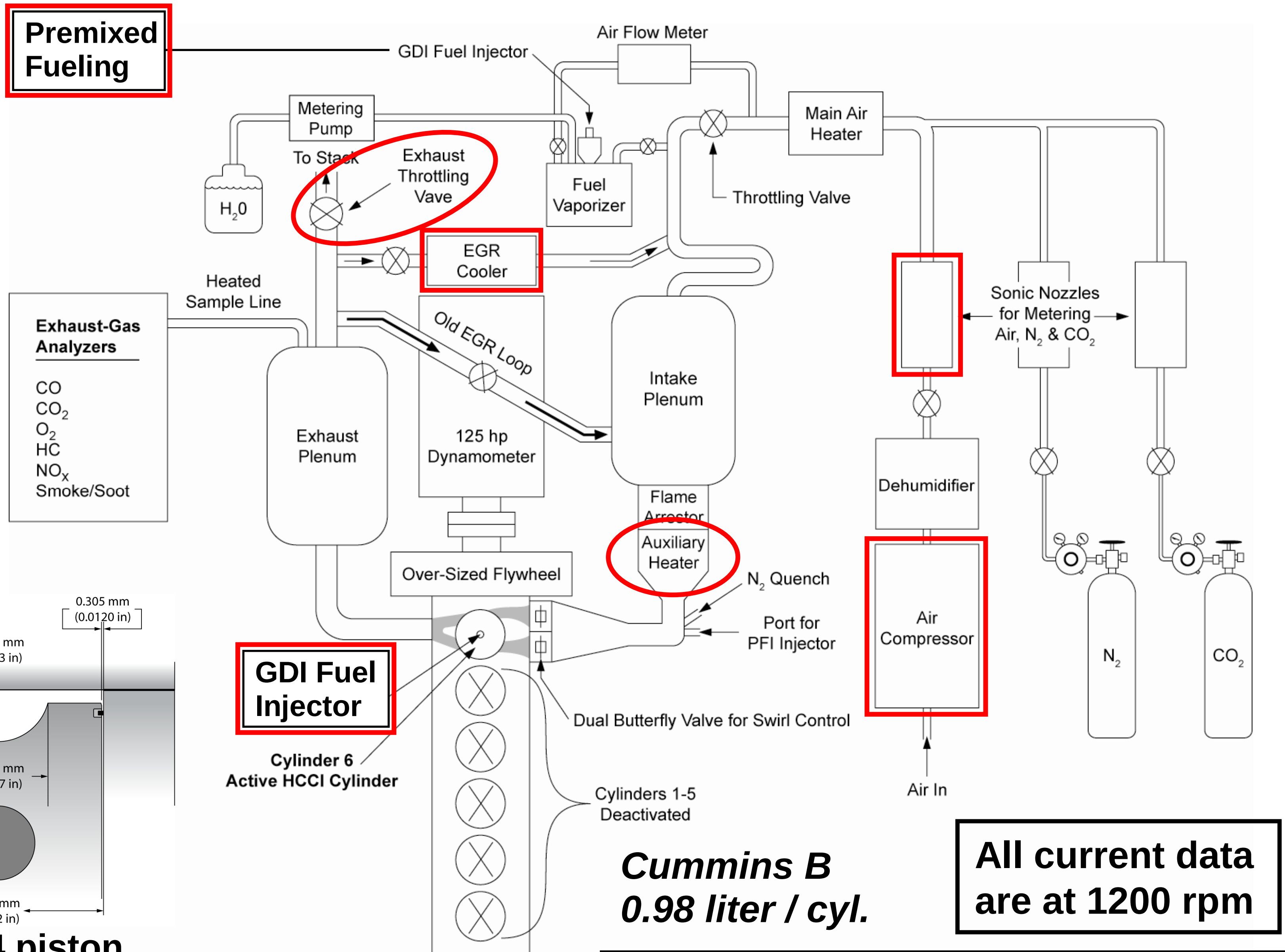
- Our boosted HCCI results show intake boosting increased autoignition reactivity of conventional gasoline, but still single-stage ignition.
  - Enhances ITHR not LTHR.

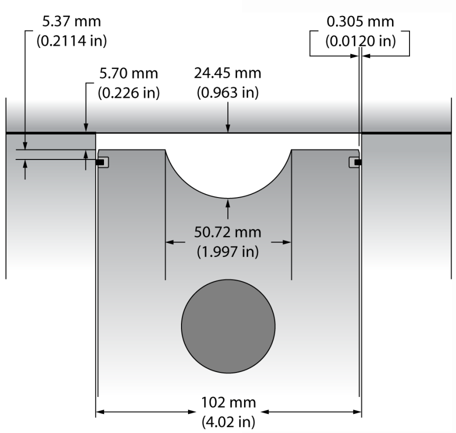
- Increased reactivity suggests fuel may become ϕ-sensitive, ⇒ may be effective for PFS.



- **<u>Objectives</u>:**
  1. Examine ϕ-sensitivity of gasoline ⇒ Naturally aspirated and Boosted.
  2. Investigate effects of PFS on HRR and PRR.
     > Vary amount of stratification ⇒ Sweep: 1) DI timing and 2) DI fraction.
  3. Investigate potential of PFS for: 1) extending high-load limit,
     2) improving efficiency of boosted HCCI.

HCCI All-Metal Engine and Subsystems





CR = 14 piston
Open Combustion Chamber

Cummins B
0.98 liter / cyl.

All current data are at 1200 rpm

Fuel is gasoline: RON = 91.7, MON = 83.4

Operation and Terminology

- For boosted operation, increasing P_{in} enhances autoignition $\Rightarrow$ overly advanced combustion, high PRR and knock.
  - Control by reducing intake temperature (T_{in}) and adding cooled EGR.
  - Minimum T_{in} = 60°C to prevent condensation of EGR-water or premixed fuel.
- For convenient comparison of data with the same charge dilution, but different EGR levels, we define:

Equivalence ratio based on total charge mass = $\phi_m = \dfrac{(F/C)}{(F/A)_{stoich}}$

- Acceptable maximum PRR varies with boost $\Rightarrow$ use ringing intensity.

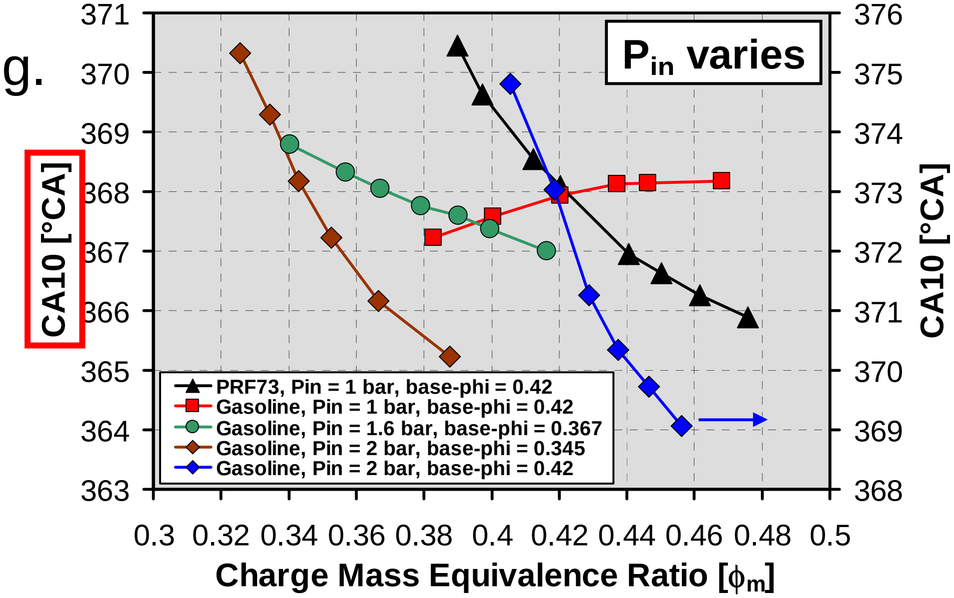
Ringing Intensity = $\dfrac{1}{2\gamma} \cdot \dfrac{\left(0.05 \cdot \left(\dfrac{dP}{dt}\right)_{\max}\right)^2}{P_{\max}} \cdot \sqrt{\gamma R T_{\max}}$

Eng, SAE 2002-01-2859

  - Knock limit taken as Ringing = 5 MW/m^2.
    $\Rightarrow$ Corresponds to 8 bar/°CA at 1200 rpm, P_{in} = 1 bar.

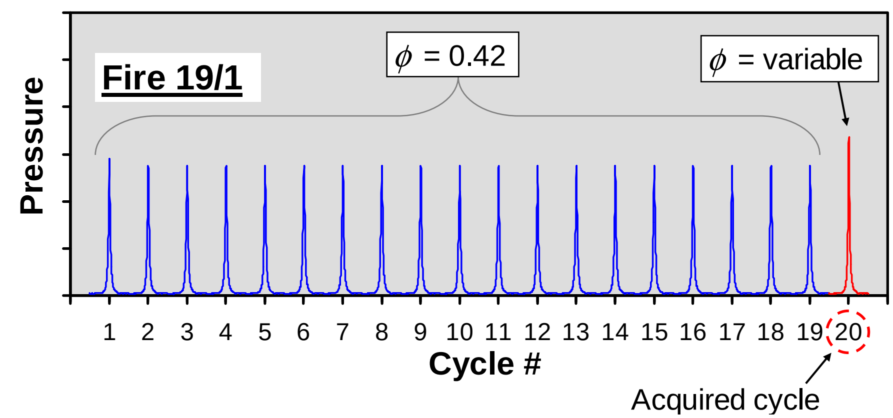
Φ-Sensitivity of Gasoline

- Use Fire19/1 technique to isolate fuel-chemistry effects from thermal effects.
  - Dec & Sjöberg *SAE 2004-01-0557*.
- Sweep ϕ above & below base fueling.
- PRF73 ⇒ 2-stage fuel with strong ϕ-sensitivity
  (Yang *et al.*, *Proc. Combst. Inst. 2011)*



Gasoline:

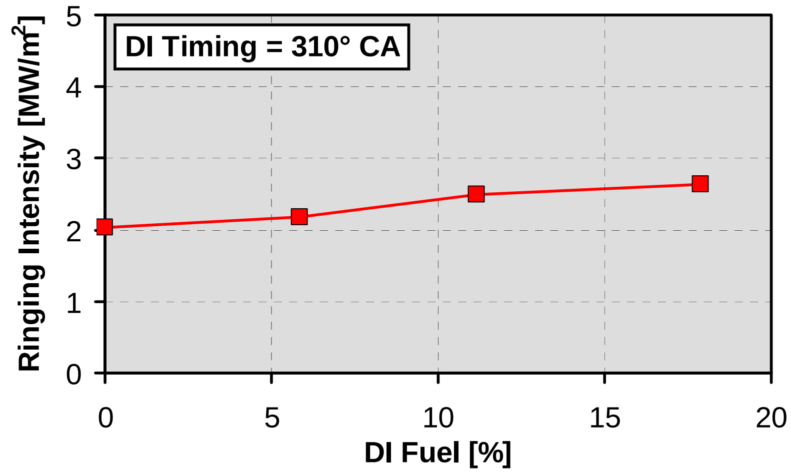
- P_{in} = 1 bar ⇒ chemistry not ϕ-sensitive, γ effect dominates.
- P_{in} = 2 bar ⇒ strong ϕ-sensitivity, more than PRF73.
- P_{in} = 1.6 bar ⇒ intermediate ϕ-sensitivity.



- Gasoline autoignition strongly ϕ-sensitive w/ boost. Not for P_{in} = 1 bar.

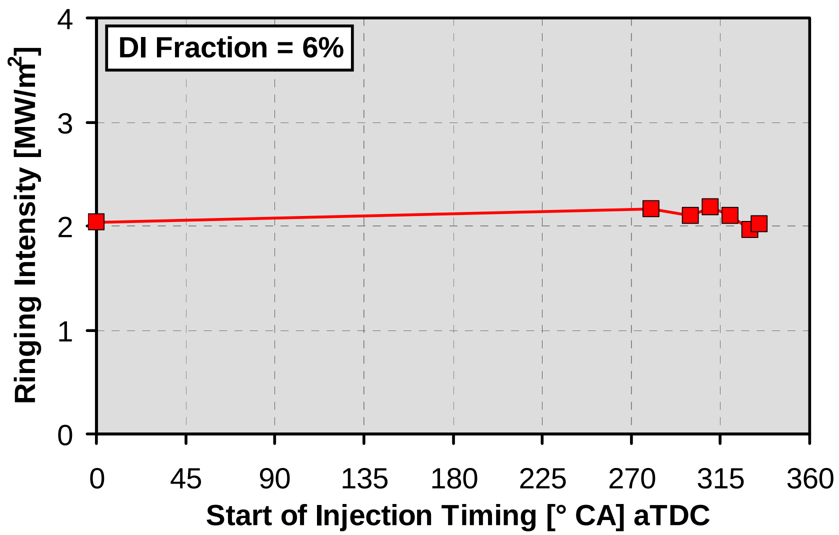
Increase Stratification for P_{in} = 1 bar

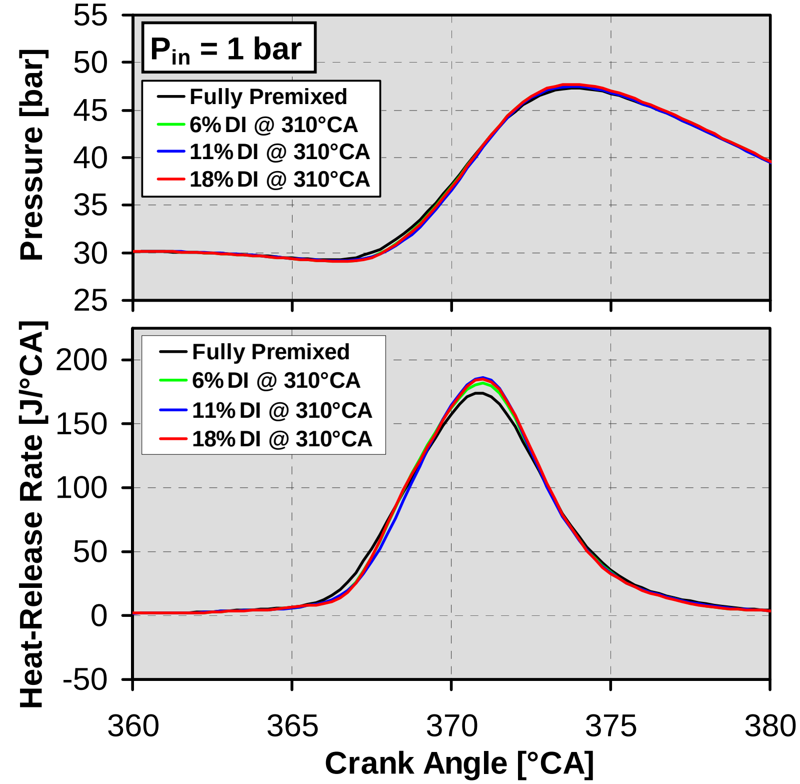
- Vary DI timing for const. 6% DI fueling.
  - Ringing ~ constant.
- Increase DI fraction; SOI = 310°CA.
  - Ringing increases slightly.



- Gasoline at P_{in} = 1 bar ⇒ PFS has no benefit for reducing max. PRR.
  - Agrees with low ϕ-sensitivity.

Hold: ϕ_m = 0.44, T_{in} = 143°C, CA50 = 371°CA

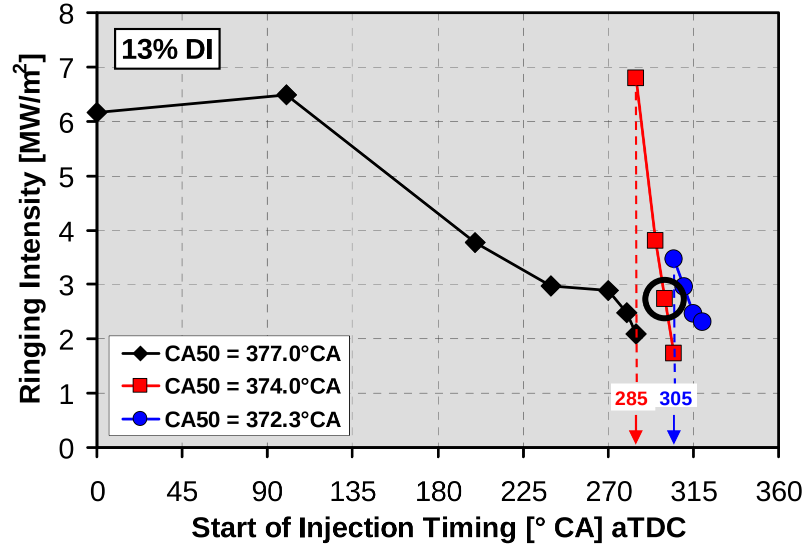


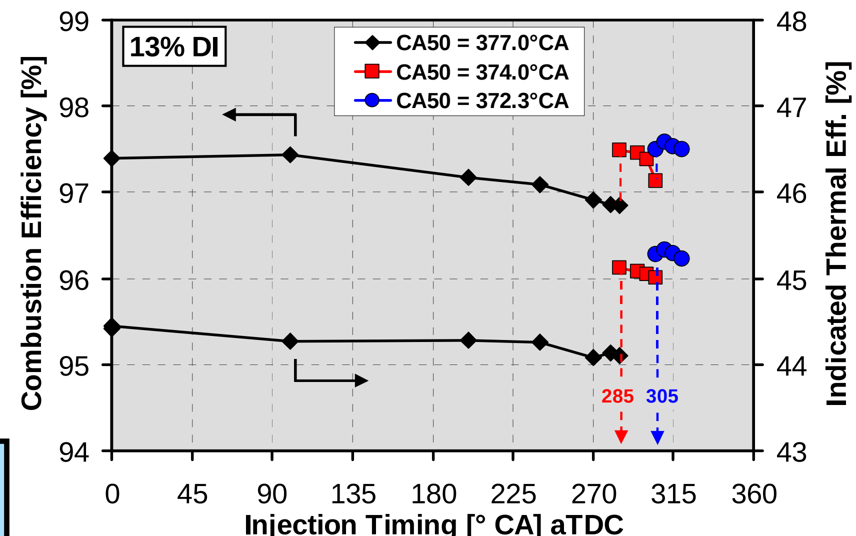


P_{in} = 2 bar: DI Timing Sweep with 13% DI

- High ϕ-sensitivity suggests PFS benefit.
- Retard DI timing to increase stratification.
  - Hold CA50 constant by varying EGR ⇒ piecewise (15.4% ≤ O_2 ≤ 14.0%).
- Dramatic reduction in ringing.
  - Initial **CA50 = 377°CA** for premixed, ringing ≈ 6 MW/m^2.
  - By SOI = 285°CA, R ≈ 2 ⇒ stability limit.
  - Advance to **CA50 = 374°CA** and further increase stratification with later SOI.
  - Advance to **372.3°CA** at SOI = 305°CA.
- Advancing CA50 improves combustion and thermal efficiencies.
- NOx and soot well below US-2010.

Hold: ϕ_m = 0.44, T_{in} = 60°C



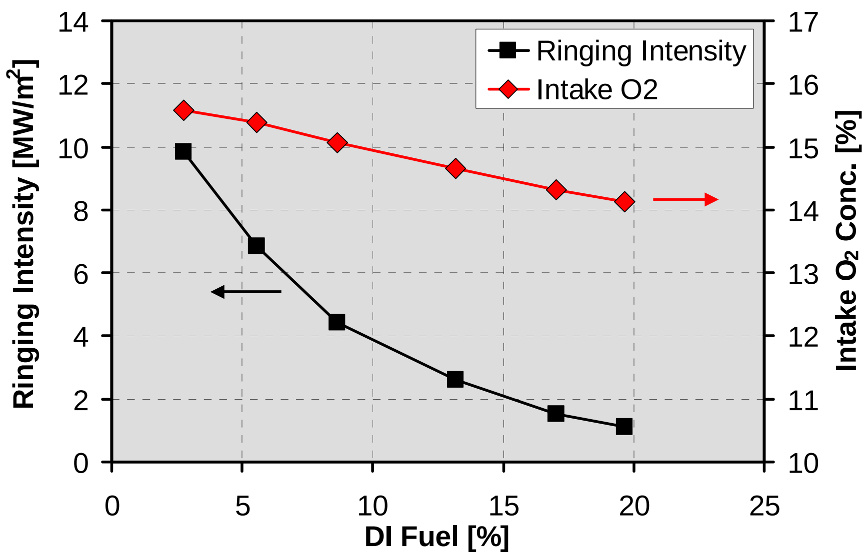


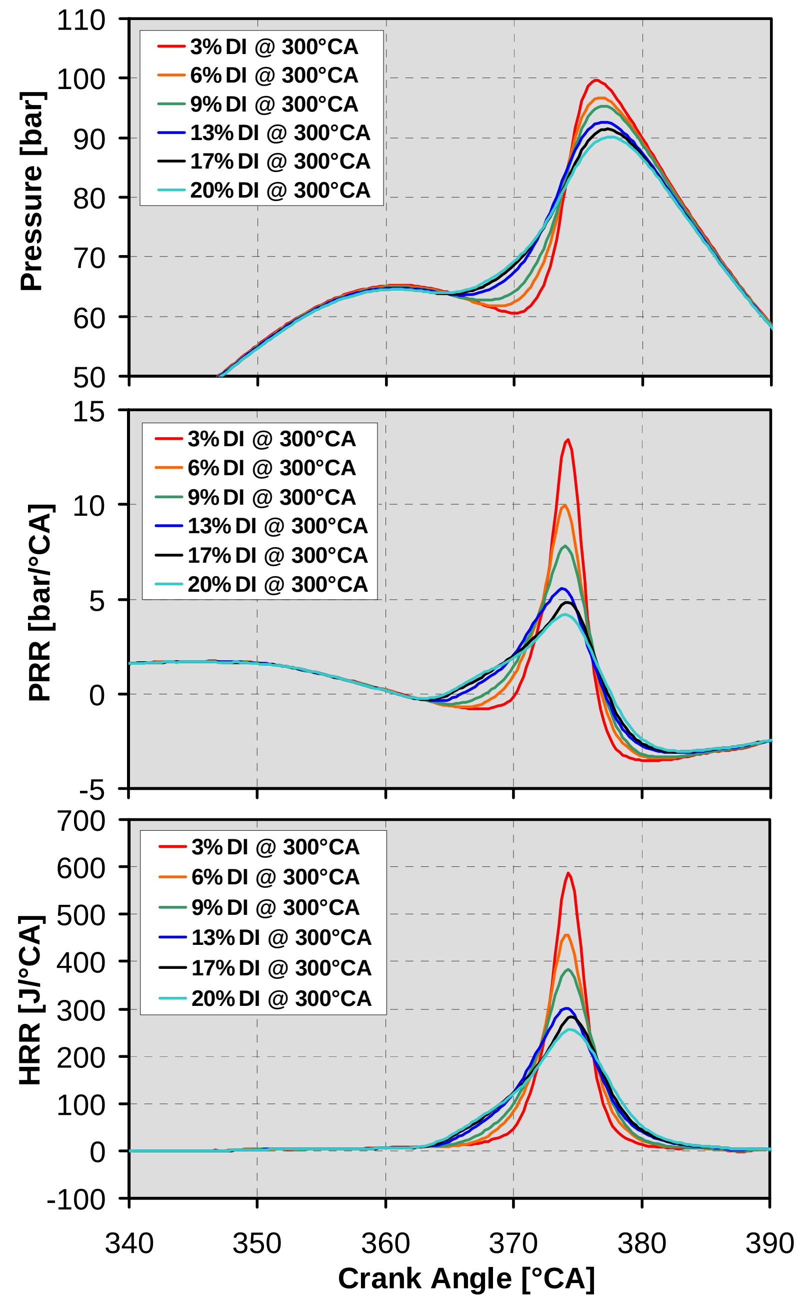
- PFS greatly reduces PRR_{max} (ringing) for gasoline boosted to P_{in} = 2 bar.

P_{in} = 2 bar: DI Fraction Sweep, SOI = 300°CA

- Large drop in ringing with increased DI%.
- Increased DI% ⇒ increased regions of higher ϕ_m ⇒ autoignite faster ⇒ advances hot ignition for same CA50.
  - Increases burn duration.
  - Reduces peak HRR, PRR_{max}, and P_{max}.
- Therm. Eff. ~ const., ultra-low NOx and soot, and COV of $IMEP_g$ < 1.5%.

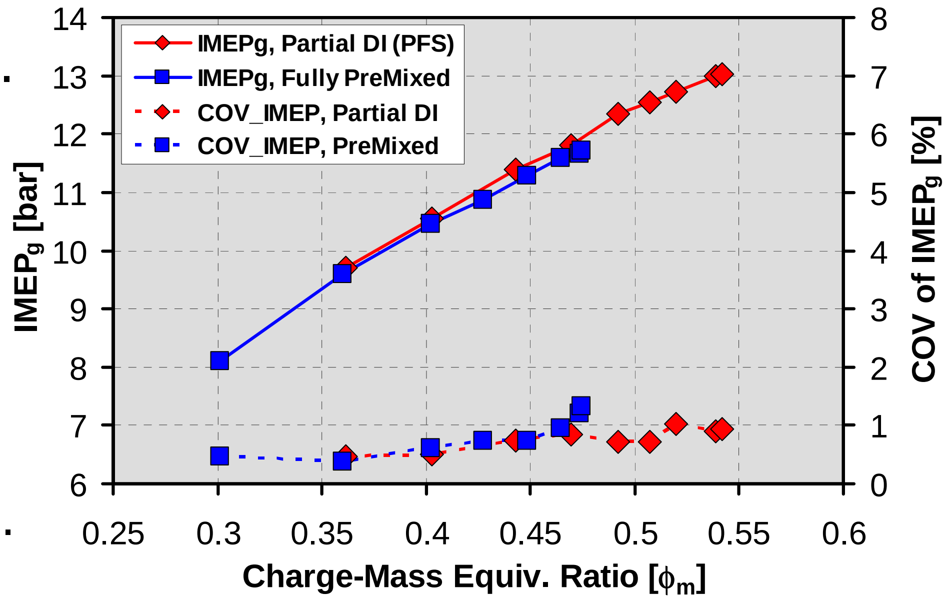
Hold: ϕ_m = 0.44, T_{in} = 60°C, CA50 = 374°CA



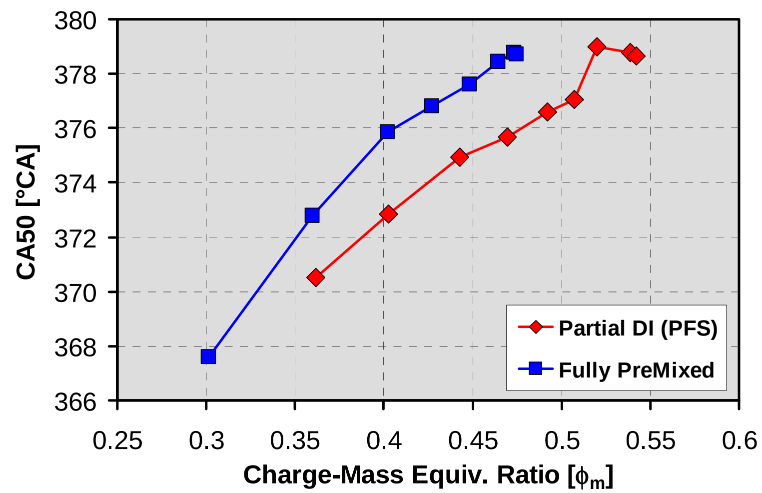


Extend High-Load Limit with PFS, P_{in} = 2 bar

- <u>Premixed fueling</u> ⇒ increase load from ϕ_m = 0.3 to knock/stability limit.
  - Retard CA50 so Ringing ≤ 5 MW/m^2 ⇒ Limit: $IMEP_g$ = 11.7 bar at ϕ_m = 0.47.



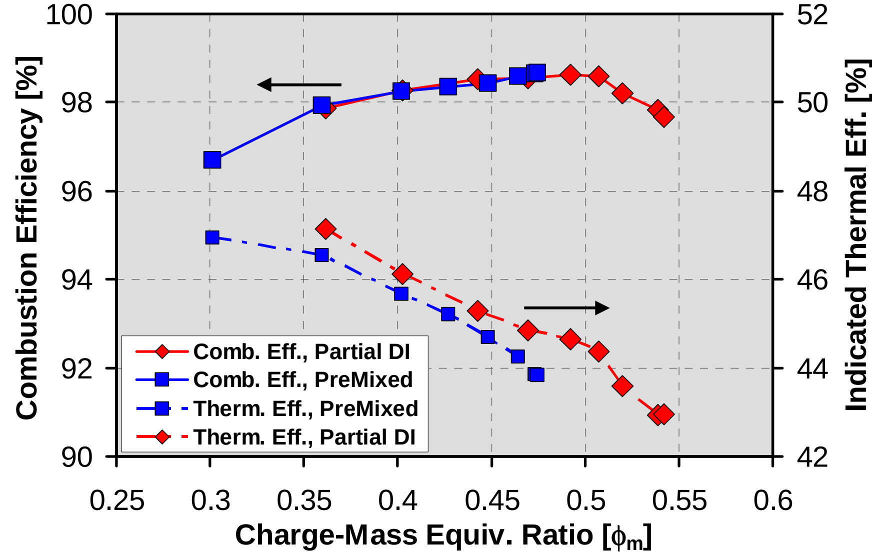
- <u>PFS</u> allows significantly higher loads.
  - Limit: $IMEP_g$ = 13.0 bar, ϕ_m = 0.54.
  - Approaching oxygen availability limit ⇒ 0.9% O_2 in exhaust.
- Large reduction of HRR (PRR) allows:
  - CA50 more advanced than premixed.
    - > Higher thermal efficiency.
  - Even with ringing of 2 to 3 MW/m^2 vs. 5 MW/m^2 for premixed.
    - > PFS more stable with lower ringing.
    - > Lower ringing ⇒ quieter.



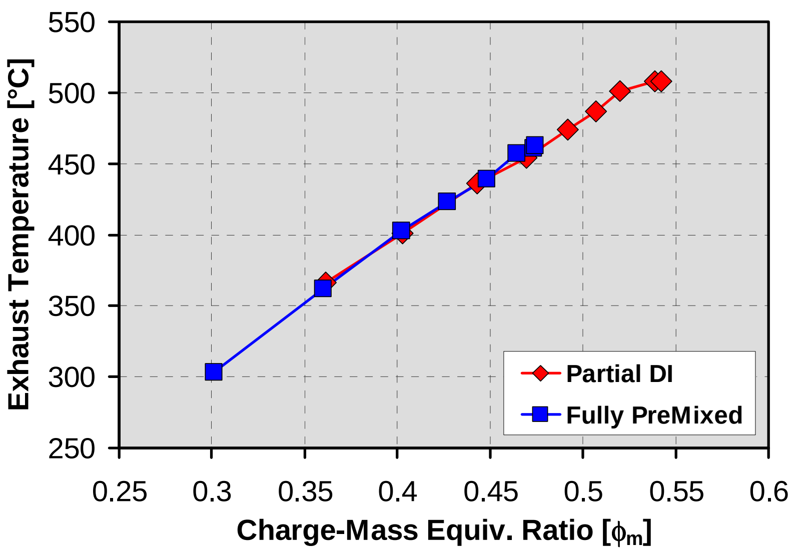
- PFS allows a large increase in load for gasoline boosted to P_{in} = 2 bar.

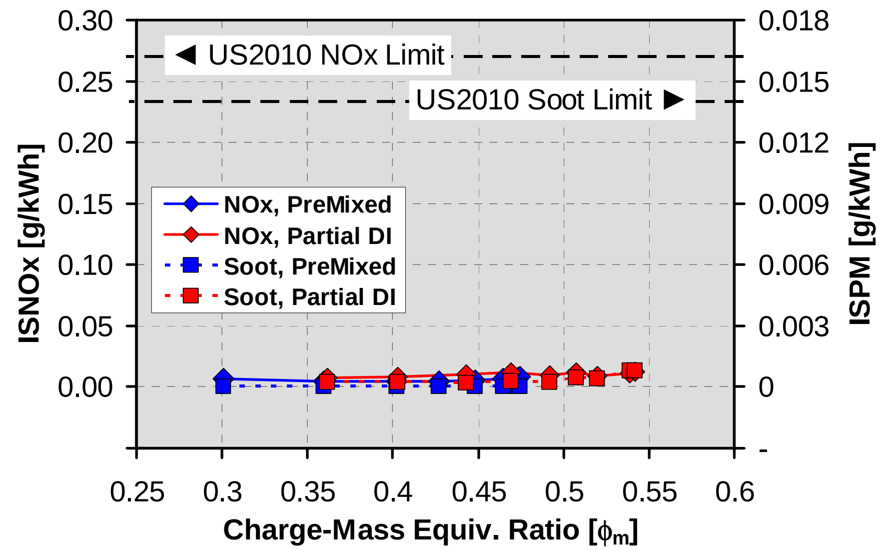
High-Load Limit with PFS, P_{in} = 2 bar

- Combst. Eff. mostly > 98%, similar to premixed.
  - Small drop at highest loads due to increased CO as O_2 becomes limited.



- Therm. Eff is higher with PFS than premixed ⇒ CA50 is less retarded.
- NO_X and soot near detectability limit.
- Exhaust reaches higher temperature ⇒ Benefits for turbo-charging.

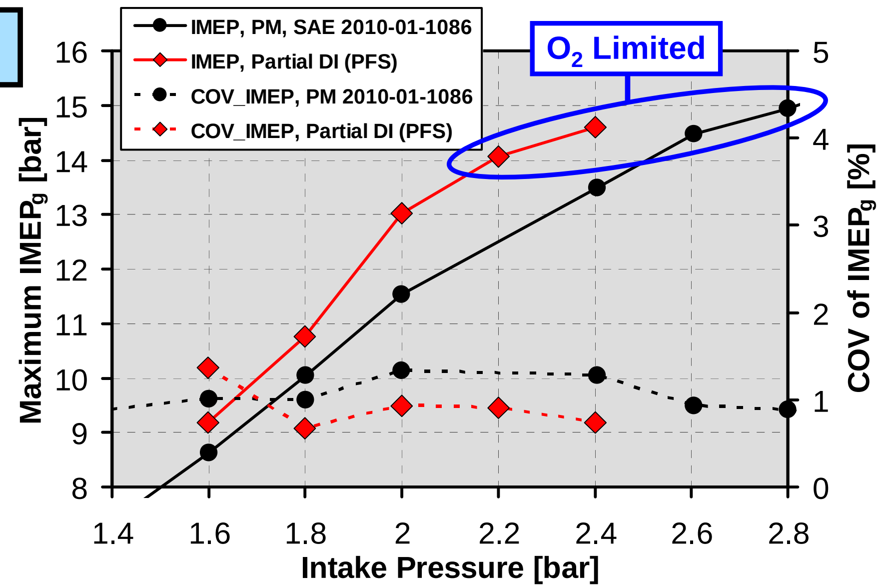


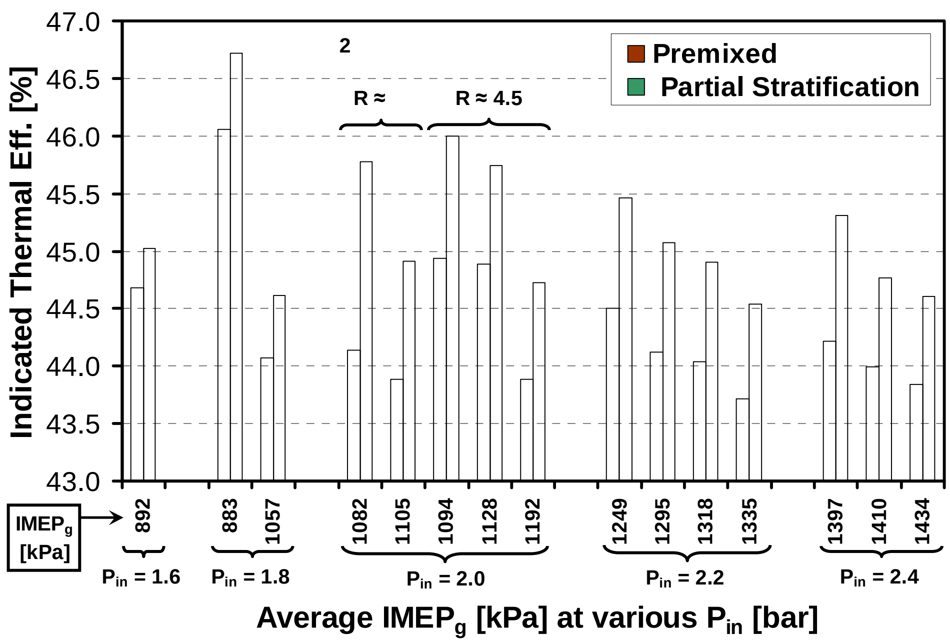


Load-Limit & Efficiency Improvements at Various P_{in}

- Our initial investigation of boosted HCCI in SAE 2010-01-1086 showed ⇒ maximum load attainable for well premixed HCCI at various boost levels.

- **PFS allows higher loads for all P_{in} tested.**
  - PFS quite stable $P_{in} \geq 2.0$ bar ⇒ largest gain.
  - O_2 limited for $P_{in} \geq 2.2$ bar.
  - PFS less stable for P_{in} = 1.6 & 1.8 bar.
    - > Lower ϕ-sensitivity.





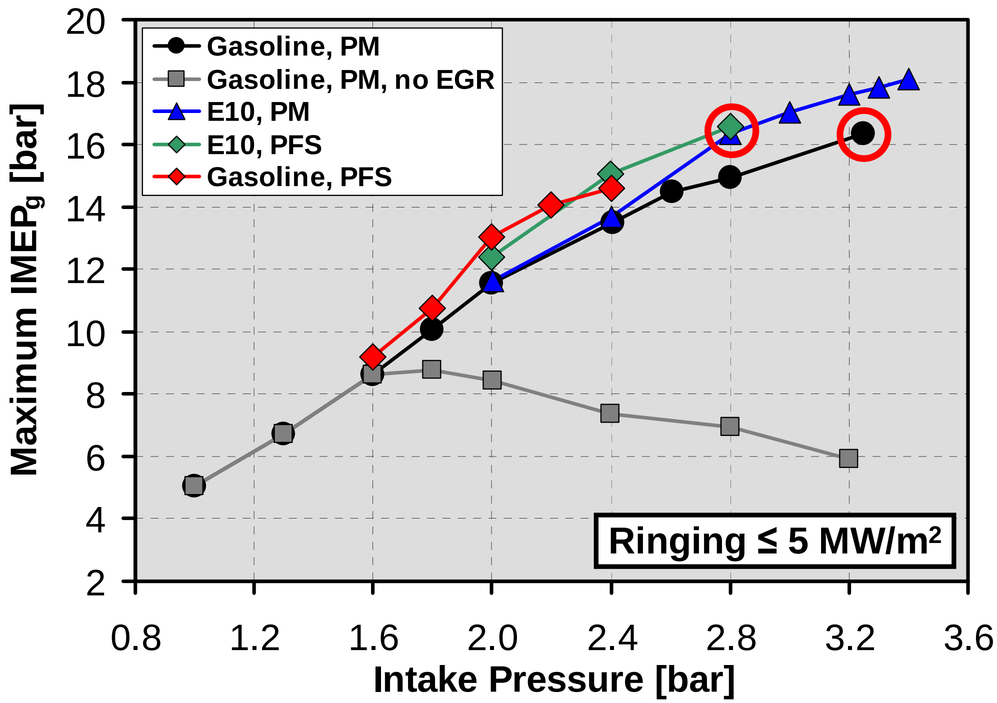
- Alternatively, for the same load, PFS allows CA50 to be advanced.

- T-E increases 0.3 to 1.6 T-E units ⇒ fuel economy gain of 0.7 – 3.6%.

- **PFS gives typical fuel economy improvement of 2 – 2.5%.**

Can E10 Increase the Oxygen-Availability Limit?

- High-load limit of ON=87 gasoline, $IMEP_g$ =16.34 bar at P_{in} = 3.25 bar.
  - Oxygen limited $P_{in} \geq$ 2.6 bar.
- E10 ⇒ Add 10% ethanol to ON=87 gasoline, ON ≈ 89.6 **≈ mid-grade pump gasoline**.
- E10 significantly reduces EGR requirement with boost.
  - More air ⇒ higher fueling
- Remains stable with timing retard ⇒ ITHR still high.



- High-load limit for E10, **$IMEP_g$ = 18.1 bar** at P_{in} = 3.4 bar.
  - Ringing ≤ 5, ultra-low NO_X & soot

- PFS works well with E10 ⇒ increase load if not O_2 limited (P_{in} ≤ 2.8 bar).
  - Obtain $IMEP_g$ = 16.6 bar with less boost ⇒ P_{in} = 2.8 bar vs. 3.25 bar for gasoline.

Conclusions

- The ϕ-sensitivity of gasoline varies substantially with intake pressure.
  - P_{in} = 1 bar $\Rightarrow$ not ϕ sensitive, and PFS is not effective for reducing the PRR.
  - P_{in} = 2 bar $\Rightarrow$ strongly ϕ sensitive, and PFS is highly effective at reducing PRR.
- For P_{in} = 2 bar, PFS extends the high-load limit to $IMEP_g$ = 13.0 bar compared to $IMEP_g$ = 11.7 bar for fully premixed fueling.
- For higher boost, P_{in} = 2.2 and 2.4 bar, PFS allows fueling to be increased to the oxygen-availability limit (EGR ~48-50%).
- PFS is effective for increasing thermal efficiencies of boosted, gasoline-fueled HCCI for P_{in} = 1.6 – 2.4 bar over a wide range of fueling rates.
  - Typically, by an amount to give fuel economy improvements of 2 – 2.5%.
- PFS also works well for E10 $\Rightarrow$ Effective range shifts to P_{in} = 2.0 – 2.8 bar.
- All PFS points examined showed extremely low NO_X and soot emissions.